ELSEVIER

Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Engineering 29 (2012) 1234 – 1238

Procedia Engineering

www.elsevier.com/locate/procedia

2012 International Workshop on Information and Electronics Engineering (IWIEE)

Research on the Bi-directional DC-DC Conversion Characterization of Ultra -capacitor Energy Storage System

ZHANG Hui-yan[a*], JING Yang[a,b], Cheng Nan[a]

[a]*College of Computer and Information Engineering, Beijing Technology and Business University, 10004,China*
[b]*Beijing Nuclear Instrument Factory, Beijing ,100176, China*

Abstract

To ensure the stability of load voltage, a bi-directional DC-DC converter is usually required in the power buffer application of the ultra-capacitor energy storage system. In this paper, non-isolated Buck-Boost bi-directional DC-DC converter is analyzed to improve the terminal voltage performances. In the light of the requirements of constant terminal voltage when positive and negative bi-directional power flows, the optimal design of power circuit and control parameters increases the operation stability of the whole ultra-capacitor energy storage system. Furthermore, it decreases the fluctuation of load voltage and raises the utilization rate of ultra-capacitors' energy reserve.

Key words: ultra-capacitor; bi-directional DC/DC converter; stability; Control Scheme

1. Introduction

As a typical energy storage device, the ultra-capacitor (UC) possesses high power density, high energy density, wide operating temperature range and quick charge-discharge features. Different from other energy storage technologies, the UC energy storage system does not require the cooling device, moving parts, customization, and it possesses of simply installation, compact conformation and easy expansion. In recent years, scholars both at home and abroad have carried out researches extensively in UC technology[1,2]. There are bright prospects for ultra-capacitor application, which can be used as either

* Corresponding author. ZhangHuiyan. Tel.:010 68985241;
E-mail address: zhanghuiy@th.btbu.edu.cn.

1877-7058 © 2011 Published by Elsevier Ltd. Open access under CC BY-NC-ND license.
doi:10.1016/j.proeng.2012.01.119

energy storage units of the power quality regulating device, auxiliary power source of electric vehicle[3], and provide voltage support for the motor speed control system[4].

For the wide range of voltage varies as the UC charging or discharging, a bi-directional DC-DC converter is usually needed as an interface circuit in the energy storage system, which could not only promote the utilization rate of ultra-capacitor energy reserve but also flexibly adjust power of ultra-capacitor.

This paper systemically analysis the operation mechanism of positive and negative power flows of the bi-directional DC-DC converter with the output voltage is constant; later study the influence relation of ultra-capacitors' larger equivalent series resistance (ESR) and power converter parameters with system stability, and provide the constraints that the stable, reliable UC energy storage system should meet. The results of simulation and experiment demonstrate the correctness and practicability of the study.

2. Power Topology and Working Principle

If the applications of UC energy storage system are not required of isolation and insulation, the non-isolated Buck-Boost bi-directional DC-DC converter will be configured in the system as shown in figure 1, which is compact, light and easily extended by multiple combinations[5].

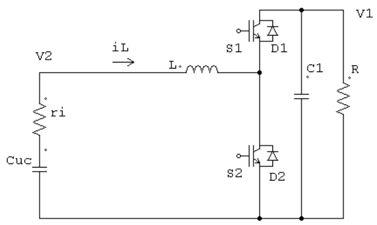


Fig 1 Topology of bi-directional DC/DC converter of UC energy storage

For single UC only can provide a lower voltage, usually need a lot of them in series parallel connection which composed a bank of UC for energy storage application. The low voltage side of v_2 is connected with the bank of UC, and the high voltage side of v_1 is connected with load or power supply. For the positive boost mode, the power energy transfer from UC bank side to v_1 by the reasonable control switch of S_2 to keep the constant load voltage by providing active power. While the negative boost mode, the power energy transfer from v_1 side to UC by the reasonable control switch of S_1.

If an inverter is connected to the v_1 side, the UC is required to provide a stable DC voltage for the inverter. Moreover, the constant level of DC voltage of v_1 imposes the direct effect on the performance of the inverter. To simplify the analysis and design, define the equivalent resistance of the inverter's load as Req. When the equivalent resistance of load is positive which is expressed as Req, meaning the inverter runs in the power supply status, and the corresponding the bi-directional power converter is in positive boost mode. Conversely， when the equivalent resistance of load is negative which is expressed as -Req , meaning the inverter runs in the energy feedback status, and the corresponding the bi-directional power converter is in negative boost mode.

In this paper, the switch S_1 and S_2 is set to complementally driving mode in an operating cycle. That make the current of inductor flows continuously and fast, which benefits to improve the dynamic response characteristic of the UC energy storage system.

3. Mathematical Model and Stability Analysis

As a time-varying, coupled nonlinear dynamic systems, it is significance that the stability of bi-directional power converter under all kinds of operational modes[6,7]. This paper analysis in detail the characteristics of positive and negative boost converter power flows of the DC converter with the output voltage v_1 is constant. As shown in Fig.1, when bi-directional converter operates in positive boost mode, supposing the turn-on time of power switching device S_2 is t_{on}, the turn-off time is t_{off}, the state variables are inductor current $i_L(t)$ and filter capacitor voltage $v_1(t)$, the average large signal model expression is provided as below.

$$\begin{cases} L\dfrac{di_L}{dt} = v_2 - r_i \times i_L - (1-d)v_1 \\ C\dfrac{dv_1}{dt} = -\dfrac{v_1}{R_{eq}} + (1-d)i_L \end{cases} \tag{1}$$

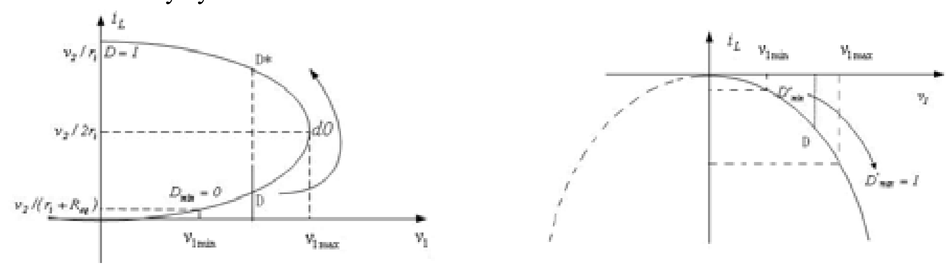
Where ri is the equivalent series resistance (ESR) of UC, d=ton/(ton+toff) is the duty cycle of the power switching device S2, and the duty cycle of S1 meets the d'=1-d.When the bi-directional converter operates at the equilibrium where $di_L(t)/dt \to 0$, $dv_1(t)/dt \to 0$ under positive boost mode, equation(2) can be easily concluded from equation(1). And when under negative boost mode, equation (3) can be also easily concluded.

$$v_2 i_L - r_i i_L^2 = \frac{v_1^2}{R_{eq}} \quad (i_L > 0) \tag{2}$$

$$v_2 i_L - r_i i_L^2 = -\frac{v_1^2}{R_{eq}} \quad (i_L < 0) \tag{3}$$

Based on power equilibrium, as shown in fig 1, the reserve capacity of UC should meet the total demand that $v_2 i_L \geq \frac{v_1^2}{R_{eq}} + r_i i_L^2$ under positive boost, and the system is stable. While under the negative boost, the charging supply energy from $v_1(t)$ should not exceed the total internal loss and the maximum possible energy storage of UC that is $-\frac{v_1^2}{R_{eq}} \geq v_2 i_L - r_i i_L^2$ ($i_L < 0$), otherwise the system is unstable.

The intersection of half solid line of elliptic curve and $v_1 < v_{1max}$ set as shown in fig 2(a) is the stable region under positive boost mode. The intersection of half solid line of hyperbolia and $v1 < v_{1max}$ set as shown in fig 2(b) is the stable region under negative boost mode. The solid line with arrow indicates the growth direction of duty cycle.



(a) (b)

Fig2 Stable operational region of bi-directional boost modes

For the positive boost, 3 kinds of working points are important corresponding the minimum duty cycle D_{min}>0 which is determined by the application requirements, the duty cycle d0 of maximum voltage gain and the region (d0,1) of pseudo-duty cycle D*. The steady voltage gain expression (4) shown as below can be derived from equation (1) easily.

$$\frac{V_1}{V_2} = \frac{(1-d)R_{eq}}{r_i + (1-d)^2 R_{eq}} \tag{4}$$

Visibly, the relationship of d and the v_1 is no monotonic. So it is required to limit the practical region of duty cycle $d \in (0,d0)$ to avoid the oscillation. For the larger ESR r_i should not be neglected, the mathematical constraint of maximum duty cycle $d0=1-(r_i/\min(R_{eq}))^{0.5}$ is obtained. As described in[8], the stability of positive boost converter would increase with inductance value decreasing and improving the minimum phase characteristics of system. So the UC energy storage system could operate stably with the constraint of power parameters $\min(R_{eq})>L/(r_iC)$ and limited range of duty cycle.

Under the negative boost mode, shown in fig 2 (b) pulse current could be absorbed by UC. If the safe voltage limit of UC arrives, the overvoltage initiated by the sustainable charging would induce the decomposition of electrolyte in UC, which could damage or decrease the life of UC and further effect the normal system operation. So combined with equation (3), to ensure the security and stability of UC energy storage system, it might be better to monitor the voltage of UC during operation and improve the power circuit shown as fig 1 with a branch leakage circuit at the side of v1 or UC.

The steady voltage gain of negative boost mode is shown as expression (4). Visibly, the relation of duty cycle d' and the voltage v_1 is monotonic.

$$\frac{V_1}{V_2} = \frac{d' R_{eq}}{d'^2 R_{eq} - r_1} \tag{5}$$

4. Simulation Results

Based on equation (1) and the corresponding average large-signal model, the state model and transfer function at an operating point of the bi-directional converter could be derived by superposition of small disturbance signals were described in[8]. A composite solution including double close-loop controllers and a feedforward based on load current detection is adopted shown in fig 3. Where VR and CR are the PI controller of the voltage loop and the current loop. To eliminate the changes influence of load on the output voltage v_1, should select the feedforward controller as $G_{io}=(T_is+1)/K_i$.

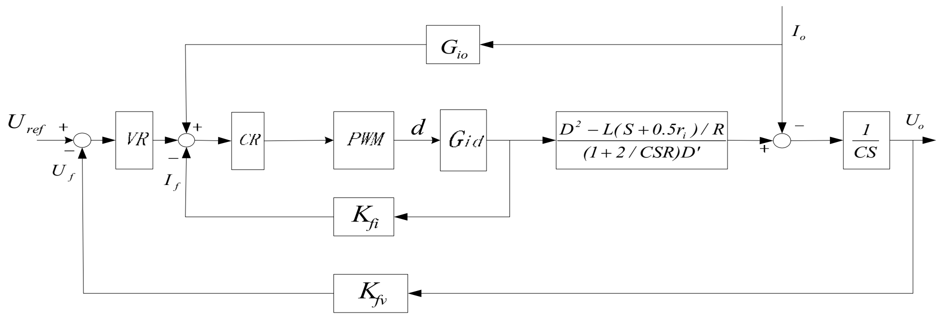


Fig3 Control diagram of converter

The parameters of UC energy storage system are set as filter inductor L=0.6mH, filter capacitor C=6.6mF, the switching frequency f=10kHz , the dc bus voltage v_1=300V while the voltage of the bank of UC v_2=55~100V, r_i=12 and the change range of duty cycle d is (0,0.95) with d0=0.96 which means the constraint of duty cycle meets. Fig 4 is the simulation result on stability of UC energy storage system, in which setting the initial voltage of the UC bank is 28v, load is 12 Ω and others are as described as above. Obviously the voltage of UC is continually dropping as discharging, and when the maximum duty cycle arrives and does not satisfy the constraints, the system would not provide firmly the required voltage support for v_1 from 1.26s.

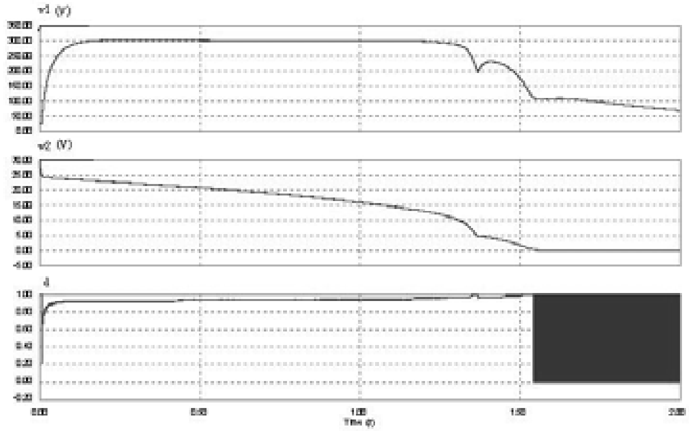


Fig4 Simulation result of converter stability

5. Conclusion

As a new type of energy storage standby power, in the area of power quality improvement and raising the utilization rate of the electric energy, the UC energy storage device has a broad developing space. According to the large ESR of UC and the possible harm of overvoltage, this paper makes a detailed analysis of the operation mechanism of UC energy storage system in the positive and negative power flows. Simulation and experiment based on these theories are carried out to explore the feasibility and stability of the UC energy storage system for improving the electric power quality of application.

References

[1] Dmitri Vinnikov, Indrek Roasto, Janis Zakis. New Bi-Directional DC/DC Converter for Supercapacitor Interfacing in High-Power Applications. 14th International Power Electronics and Motion Control Conference, EPE-PEMC 2010, T11-39-43

[2] Diego Iannuzzi, Pietro Tricoli. Optimal Control Strategy of Onboard Supercapacitor Storage System for Light Railway Vehicles[C]. IEEE International Symposium on Industrial Electronics, 2010:280-285.

[3] Caricchi, F. et al. Study of bidirectional buck-boost converter topologies for application in EV drives. Applied Power Electronics Conference and Exposition, 1998, 1(1):287-293.

[4] Xu aiguo,Xie shaojun, Yao yuan et al. Regenerating Energy Storage System Based on UC for Urban Railway Vehicles. Transactions of China Electrotechnical Society, 2010，25 (3) :117-123.

[5] Attaianese C,Nardi V,Tomasso G. High performances supercapacitor recovery system for industrial drive applications[C].Applied Power Electronics Conference and Exposition, Anaheim,California,2004:1635-1641.

[6] Zhu chenghua, Yan yangguang. Stability and Dynamics of BOOST Converter with Constant Power Load. JOURNAL OF NANJING UNIVERSITY OF AERONAUTICS & ASTRONAUTICS, 2005，37 (1)： 20-24.

[7] Yan-Fei Liu; Sen, P.C.;Large-signal modeling of hysteretic current-programmed converters.IEEE Transactions on Power Electronics, 1996 11(3):423-430.

[8] Zhang huiyan. Research on the Analysis and Control Strategy of Ultracapacitor DC Storage Energy System Application. Graduate University of Chinese Academy of Sciences(NSTITUTE OF ELECTRICAL ENGINEERING),2006.